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(REV 12-29-99)

U.S. DEPARTMENT OF COMMERCE PATENT AND TRADEMARK OFFICE

ATTORNEY'S DOCKET NUMBER

TRANSMITTAL LETTER TO THE UNITED STATES
DESIGNATED/ELECTED OFFICE (DO/EO/US)
CONCERNING A FILING UNDER 35 U.S.C. 371

GORE/MU/192/PCT/US

U.S. APPLICATION NO. (If known, see 37 CFR 1.52)
09/509849INTERNATIONAL APPLICATION NO.
PCT/US98/18938INTERNATIONAL FILING DATE
11-September-1998PRIORITY DATE CLAIMED
11-September-1997TITLE OF INVENTION **A METHOD OF DEPOSITING AN ELECTROCATALYST AND ELECTRODES FORMED BY SUCH METHOD**

APPLICANT(S) FOR DO/EO/US

Gore Enterprise Holdings, Inc.

Applicant herewith submits to the United States Designated/Elected Office (DO/EO/US) the following items and other information:

1. ☒ This is a **FIRST** submission of items concerning a filing under 35 U.S.C. 371.
2. ☐ This is a **SECOND** or **SUBSEQUENT** submission of items concerning a filing under 35 U.S.C. 371.
3. ☐ This express request to begin national examination procedures (35 U.S.C. 371(f)) at any time rather than delay examination until the expiration of the applicable time limit set in 35 U.S.C. 371(b) and PCT Articles 22 and 39(1).
4. ☒ A proper Demand for International Preliminary Examination was made by the 19th month from the earliest claimed priority date.
5. ☒ A copy of the International Application as filed (35 U.S.C. 371(c)(2))
 - a. ☐ is transmitted herewith (required only if not transmitted by the International Bureau).
 - b. ☐ has been transmitted by the International Bureau.
 - c. ☐ is not required, as the application was filed in the United States Receiving Office (RO/US).
6. ☐ A translation of the International Application into English (35 U.S.C. 371(c)(2)).
7. ☐ Amendments to the claims of the International Application under PCT Article 19 (35 U.S.C. 371(c)(3))
 - a. ☐ are transmitted herewith (required only if not transmitted by the International Bureau).
 - b. ☐ have been transmitted by the International Bureau.
 - c. ☐ have not been made; however, the time limit for making such amendments has NOT expired.
 - d. ☐ have not been made and will not be made.
8. ☐ A translation of the amendments to the claims under PCT Article 19 (35 U.S.C. 371(c)(3)).
9. ☐ An oath or declaration of the inventor(s) (35 U.S.C. 371(c)(4)).
10. ☐ A translation of the annexes to the International Preliminary Examination Report under PCT Article 36 (35 U.S.C. 371(c)(5)).

Items 11. to 16. below concern document(s) or information included:

11. ☐ An Information Disclosure Statement under 37 CFR 1.97 and 1.98.
12. ☐ An assignment document for recording. A separate cover sheet in compliance with 37 CFR 3.28 and 3.31 is included.
13. ☒ A **FIRST** preliminary amendment.
☐ A **SECOND** or **SUBSEQUENT** preliminary amendment.
14. ☐ A substitute specification.
15. ☐ A change of power of attorney and/or address letter.
16. ☒ Other items or information:

Petition for Revival of An International Application for Patent Designating the U.S. Abandoned Unintentionally under 37 C.F.R. § 1.137(b) and the filing fee in the amount of \$1,210.00**Check number 1309 in the total amount of \$3,758.00 comprising the following fees:****Petition for Revival \$1,210.00, plus the Preliminary Examination fee and application filing fees of \$2,548.00**

09/509849-791300

U.S. APPLICATION NO. (if known, see 37 CFR 1.5)

INTERNATIONAL APPLICATION NO.
PCT/US98/18938ATTORNEY'S DOCKET NUMBER
GORE/MI/192/PCT/US

02/509849

17. ☒ The following fees are submitted:

BASIC NATIONAL FEE (37 CFR 1.492 (a) (1) - (5)) :

Neither international preliminary examination fee (37 CFR 1.482)
nor international search fee (37 CFR 1.445(a)(2)) paid to USPTO
and International Search Report not prepared by the EPO or JPO \$970.00International preliminary examination fee (37 CFR 1.482) not paid to
USPTO but International Search Report prepared by the EPO or JPO \$840.00International preliminary examination fee (37 CFR 1.482) not paid to USPTO but
international search fee (37 CFR 1.445(a)(2)) paid to USPTO \$690.00International preliminary examination fee paid to USPTO (37 CFR 1.482)
but all claims did not satisfy provisions of PCT Article 33(1)-(4) \$670.00International preliminary examination fee paid to USPTO (37 CFR 1.482)
and all claims satisfied provisions of PCT Article 33(1)-(4) \$96.00

ENTER APPROPRIATE BASIC FEE AMOUNT = \$ 670.00

Surcharge of \$130.00 for furnishing the oath or declaration later than ☐ 20 ☐ 30
months from the earliest claimed priority date (37 CFR 1.492(e)). \$

CLAIMS	NUMBER FILED	NUMBER EXTRA	RATE		
Total claims	100 - 20 =	22	X \$18.00	\$	1800.00
Independent claims	4 - 3 =	1	X \$78.00	\$	78.00
MULTIPLE DEPENDENT CLAIM(S) (if applicable)			+ \$260.00	\$	

TOTAL OF ABOVE CALCULATIONS = \$ 2548.00

Reduction of 1/2 for filing by small entity, if applicable. A Small Entity Statement
must also be filed (Note 37 CFR 1.9, 1.27, 1.28). \$

SUBTOTAL = \$ 2548.00

Processing fee of \$130.00 for furnishing the English translation later than ☐ 20 ☐ 30
months from the earliest claimed priority date (37 CFR 1.492(f)). \$

TOTAL NATIONAL FEE = \$

Fee for recording the enclosed assignment (37 CFR 1.21(h)). The assignment must be
accompanied by an appropriate cover sheet (37 CFR 3.28, 3.31). \$40.00 per property + \$

TOTAL FEES ENCLOSED = \$ 2548.00

Amount to be
refunded: \$
charged: \$

- a. ☒ A check in the amount of \$ 2548.00 to cover the above fees is enclosed.
- b. ☐ Please charge my Deposit Account No. _____ in the amount of \$ _____ to cover the above fees.
A duplicate copy of this sheet is enclosed.
- c. ☒ The Commissioner is hereby authorized to charge any additional fees which may be required, or credit any
overpayment to Deposit Account No. 50-0997. A duplicate copy of this sheet is enclosed.

NOTE: Where an appropriate time limit under 37 CFR 1.494 or 1.495 has not been met, a petition to revive (37 CFR 1.137(a) or (b)) must be filed and granted to restore the application to pending status.

SEND ALL CORRESPONDENCE TO:

Paula D. Morris & Associates, P.C.
2925 Briarpark Drive, Suite 930
Houston, Texas 77042-3728

SIGNATURE:

Paula D. Morris

NAME

31,516

REGISTRATION NUMBER

09/509849

430 Rec'd PCT/PTO 03 APR 2000

IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

In re Application of:	§	Group Art Unit:
Dearnaley, et al.	§	
	§	
Serial No.:	§	
	§	Examiner: B. Talbot
Filed:	§	
	§	
For: A Method of Depositing an	§	
Electrocatalyst and Electrodes	§	Atty. Docket: GORE/MI/192/PCT/US
Formed Thereby	§	

PRELIMINARY AMENDMENT

Attention: PCT Legal Staff
 Box PCT
 Assistant Commissioner for Patents
 Washington, D.C. 20231

Please make the following preliminary amendments to the referenced application before examining this case.

AMENDMENTS

Please delete the title and insert therefor --CATALYTIC COATINGS AND FUEL CELL ELECTRODES AND MEMBRANE ELECTRODE ASSEMBLIES MADE THEREFROM--.

Please cancel claims 2-47

Please add the following new claims:

-- 48. A method for making a fuel cell electrode comprising:

providing one or more vaporizable noble metals;

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thermally converting said one or more vaporizable noble metals into a vapor; and
depositing said vapor onto a gas permeable support in an amount sufficient to
produce a catalytically effective load consisting essentially of said one or
more noble metals on said support. --

-- 49. The method of claim 48 wherein at least said depositing occurs in a
vacuum. --

-- 50. The method of claim 48 wherein said support is a carbon catalyst
support. --

-- 51. The method of claim 49 wherein said support is a carbon catalyst
support. --

-- 52. The method of claim 50 wherein said carbon catalyst support comprises a
material selected from the group consisting of a carbon filament bundle, reticulated carbon,
carbon cloth, and carbon mesh. --

-- 53. The method of claim 51 wherein said carbon catalyst support comprises a
material selected from the group consisting of a carbon filament bundle, reticulated carbon,
carbon cloth, and carbon mesh.

-- 54. The method of claim 48 wherein said support comprises a membrane
comprising a composite of polytetrafluoroethylene comprising impregnated ion exchange
media, said composite comprising a thickness of about 1 μm . --

-- 55. The method of claim 49 wherein said support comprises a membrane comprising a composite of polytetrafluoroethylene comprising impregnated ion exchange media, said composite comprising a thickness of about 1 μm . --

-- 56. The method of claim 48 wherein said one or more noble metals comprises one or more metals selected from the group consisting of platinum, gold, silver, palladium, ruthenium, rhodium, iridium. --

-- 57. The method of claim 49 wherein said one or more noble metals comprises one or more metals selected from the group consisting of platinum, gold, silver, palladium, ruthenium, rhodium, iridium. --

-- 58. The method of claim 50 wherein said one or more noble metals comprises one or more metals selected from the group consisting of platinum, gold, silver, palladium, ruthenium, rhodium, iridium. --

-- 59. The method of claim 51 wherein said one or more noble metals comprises one or more metals selected from the group consisting of platinum, gold, silver, palladium, ruthenium, rhodium, iridium. --

-- 60. The method of claim 54 wherein said one or more catalytic components comprises one or more metals selected from the group consisting of platinum, gold, silver, palladium, ruthenium, rhodium, iridium. --

-- 61. The method of claim 55 wherein said one or more catalytic components comprises one or more metals selected from the group consisting of platinum,

gold, silver, palladium, ruthenium, rhodium, iridium. --

-- 62. The method of claim 48 wherein said load comprises less than about 0.3 mg/cm². --

-- 63. The method of claim 48 wherein said load comprises less than about 0.2 mg/cm². --

-- 64. The method of claim 48 wherein said load comprises from about 0.01 to about 0.2 mg/cm². --

-- 65. The method of claim 49 wherein said load comprises less than about 0.3 mg/cm². --

-- 66. The method of claim 49 wherein said load comprises less than about 0.2 mg/cm². --

-- 67. The method of claim 49 wherein said load comprises from about 0.01 to about 0.2 mg/cm². --

-- 68. The method of claim 50 wherein said load comprises less than about 0.3 mg/cm².

-- 69. The method of claim 50 wherein said load comprises less than about 0.2 mg/cm². --

-- 70. The method of claim 50 wherein said load comprises from about 0.01 to about 0.2 mg/cm². --

-- 71. The method of claim 51 wherein said load comprises less than about 0.3 mg/cm².

-- 72. The method of claims 51 wherein said load comprises less than about 0.2 mg/cm². --

-- 73. The method of claim 51 wherein said load comprises from about 0.01 to about 0.2 mg/cm². --

-- 74. The method of claim 54 wherein said load comprises less than about 0.3 mg/cm². --

-- 75. The method of claims 54 wherein said load comprises less than about 0.2 mg/cm². --

-- 76. The method of claim 54 wherein said load comprises from about 0.01 to about 0.2 mg/cm². --

-- 77. The method of claim 55 wherein said load comprises less than about 0.3 mg/cm². --

-- 78. The method of claims 55 wherein said load comprises less than about 0.2 mg/cm². --

-- 79. The method of claim 55 wherein said load comprises from about 0.01 to about 0.2 mg/cm². --

-- 80. The method of claim 48 wherein said one or more noble metals

comprise platinum. --

-- 81. The method of claim 62 wherein said one or more noble metals
comprise platinum. --

-- 82. The method of claim 63 wherein said one or more noble metals
comprise platinum. --

-- 83. The method of claim 64 wherein said one or more noble metals
comprise platinum. --

-- 84. The method of claim 48 wherein said support is a coating on a carbon
cloth, wherein said coating is selected from the group consisting of carbon, a wet proofing
material, and a combination thereof. --

-- 85. The method of claim 62 wherein said support is a coating on a carbon
cloth, wherein said coating is selected from the group consisting of carbon, a wet proofing
material, and a combination thereof. --

-- 86. The method of claim 85 wherein said wet proofing material is
polytetra-fluoroethylene.

-- 87. The method of claim 62 further comprising

providing a solid polymer electrolyte membrane; and

disposing said support in ionic communication with said solid polymer electrolyte
membrane. --

-- 88. The method of claim 87 wherein

said solid polymer electrolyte membrane has a first side and a second side opposite said first side, and

said method further comprises disposing said support on each of said first side and said second side to produce a membrane electrode assembly.

-- 89. The method of claim 62 further comprising

providing a solid polymer electrolyte membrane; and

disposing said support in ionic communication with said solid polymer electrolyte membrane.

-- 90. The method of claim 89 wherein

said solid polymer electrolyte membrane has a first side and a second side opposite said first side, and

said method further comprises disposing said support on each of said first side and said second side to produce a membrane electrode assembly. --

-- 91. The method of claim 48 wherein said thermally converting comprises converting using electron-beam physical vapor deposition. --

-- 92. A fuel cell electrode produced by a process comprising:

providing one or more vaporizable noble metals;

thermally converting said one or more noble metals into a vapor; and

depositing said vapor onto a gas permeable support in an amount sufficient to produce a catalytically effective load consisting essentially of said one or more noble metals on said support. --

-- 93. The fuel cell electrode of claim 92 wherein at least said depositing occurs in a vacuum. --

-- 94. The fuel cell electrode of claim 93 wherein said support is a carbon catalyst support. --

-- 95. The fuel cell electrode of claim 94 wherein said support is a carbon catalyst support comprising a material selected from the group consisting of a carbon filament bundle, reticulated carbon, carbon cloth, and carbon mesh. --

-- 96. The fuel cell electrode of claim 95 wherein said carbon catalyst support comprises a material selected from the group consisting of a carbon cloth and a coating on a carbon cloth selected from the group consisting of carbon, a wet proofing material, and a combination thereof. --

-- 97. The fuel cell electrode of claim 92 wherein said support comprises a membrane comprising a composite of polytetrafluoroethylene comprising impregnated ion exchange media, said composite comprising a thickness of about 1 μm . --

-- 98. The fuel electrode of claim 92 wherein said one or more noble metals

are selected from the group consisting of platinum, gold, silver, palladium, ruthenium, rhodium, iridium. --

-- 99. The fuel electrode of claim 94 wherein said one or more noble metals are selected from the group consisting of platinum, gold, silver, palladium, ruthenium, rhodium, iridium. --

-- 100. The fuel cell electrode of claim 92 wherein said one or more noble metals comprises platinum. --

-- 101. The fuel cell electrode of claim 94 wherein said one or more noble metals comprises platinum. --

-- 102. The fuel cell electrode of claim 96 wherein said one or more noble metals comprises platinum. --

-- 103. The fuel cell electrode of claim 97 wherein said one or more noble metals comprises platinum.

-- 104. The fuel cell electrode of claim 96 wherein said wet proofing material is polytetra-fluoroethylene. --

-- 105. The fuel cell electrode of claim 92 wherein said thermally converting comprises converting using electron-beam physical vapor deposition. --

-- 106. The fuel cell electrode of claim 100 wherein, at a cell potential of about 0.6 V, an MEA containing said electrode half cell operating as a cathode yields about

800 mA cm⁻² or greater. --

-- 107. The fuel cell electrode of claim 101 wherein, at a cell potential of about 0.6 V, an MEA containing said electrode half cell operating as a cathode yields about 800 mA cm⁻² or greater. --

-- 108. The fuel cell electrode of claim 102 wherein, at a cell potential of about 0.6 V, an MEA containing said electrode half cell operating as a cathode yields about 800 mA cm⁻² or greater. --

-- 109. The fuel cell electrode of claim 103 wherein, at a cell potential of about 0.6 V, an MEA containing said electrode half cell operating as a cathode yields about 800 mA cm⁻² or greater. --

-- 110. The fuel cell electrode of claims 106 wherein said electrode comprises an electrocatalytic active area of about 300 cm² or greater. --

-- 111. The fuel cell electrode of claims 107 wherein said electrode comprises an electrocatalytic active area of about 300 cm² or greater. --

-- 112. The electrode of claims 108 wherein said electrode comprises an electrocatalytic active area of about 300 cm² or greater. --

-- 113. The electrode of claims 109 wherein said electrode comprises an electrocatalytic active area of about 300 cm² or greater. --

-- 114. A fuel cell electrode comprising a support comprising a deposit

disposed thereon, said deposit comprising a catalytically effective load of an electrocatalyst comprising an electrocatalytic active area at least in part comprising rod-shaped structures. -

-- 115. The electrode of claim 114 wherein said rod-like structures are visible at a magnification of at least about x10k. --

-- 116. The electrode of claim 114 wherein said deposit further comprises particles of said electrocatalyst comprising an outer surface, wherein said electrocatalytic active area comprises a majority of said outer surface of said particles. --

-- 117. The electrode of claim 115 wherein said deposit further comprises particles of said electrocatalyst comprising an outer surface, wherein said electrocatalytic active area comprises a majority of said outer surface of said particles.--

-- 118. The electrode of claim 114 wherein said load comprises less than about 0.3 mg/cm^2 . --

-- 119. The electrode of claims 114 herein said load comprises less than about 0.2 mg/cm^2 . --

-- 120. The electrode of claim 114 wherein said load comprises from about 0.01 to about 0.2 mg/cm^2 . --

-- 121. The electrode of claim 115 wherein said load comprises less than about 0.3 mg/cm^2 . --

-- 122. The electrode of claims 115 herein said load comprises less than about 0.2 mg/cm². --

-- 123. The electrode of claim 115 wherein said load comprises from about 0.01 to about 0.2 mg/cm². --

-- 124. The electrode of claim 117 wherein said load comprises less than about 0.3 mg/cm². --

-- 125. The electrode of claims 117 herein said load comprises less than about 0.2 mg/cm². --

-- 126. The electrode of claim 117 wherein said load comprises from about 0.01 to about 0.2 mg/cm². --

-- 127. The electrode of claims 114 wherein said support has a surface area, and said deposit covers about 300 cm² or more of said surface area. --

-- 128. The electrode of claim 118 wherein said support has a surface area, and said deposit covers about 300 cm² or more of said surface area. --

-- 129. The electrode of claims 121 wherein said support has a surface area, and said deposit covers about 300 cm² or more of said surface area. --

-- 130. The electrode of claims 124 wherein said support has a surface area, and said deposit covers about 300 cm² or more of said surface area. --

-- 131. The electrode of claim 114 wherein said electrocatalyst comprises

platinum. --

-- 132. The electrode of claim 118 wherein said electrocatalyst comprises platinum. --

-- 133. The electrode of claim 121 wherein said electrocatalyst comprises platinum. --

-- 134. The electrode of claim 124 wherein said electrocatalyst comprises platinum. --

-- 135. The electrode of claim 130 wherein said electrocatalyst comprises platinum. --

-- 136. The electrode of claim 130 wherein, at a cell potential of about 0.6 V, an MEA containing said electrode as a half cell operating as a cathode yields a power output of about 800 mA cm^{-2} or greater. --

-- 137. The electrode of claim 131 wherein, at a cell potential of about 0.6 V, an MEA containing said electrode as a half cell operating as a cathode yields a power output of about 800 mA cm^{-2} or greater. --

-- 138. The electrode of claim 132 wherein, at a cell potential of about 0.6 V, an MEA containing said electrode as a half cell operating as a cathode yields a power output of about 800 mA cm^{-2} or greater. --

-- 139. The electrode of claim 133 wherein, at a cell potential of about 0.6 V,

an MEA containing said electrode as a half cell operating as a cathode yields a power output of about 800 mA cm^{-2} or greater. --

-- 140. The electrode of claim 134 wherein, at a cell potential of about 0.6 V, an MEA containing said electrode as a half cell operating as a cathode yields a power output of about 800 mA cm^{-2} or greater. --

-- 141. The electrode of claim 135 wherein, at a cell potential of about 0.6 V, an MEA containing said electrode as a half cell operating as a cathode yields a power output of about 800 mA cm^{-2} or greater.

-- 142. A membrane electrode assembly comprising the fuel cell electrode of claim 114. --

-- 143. A membrane electrode assembly comprising the fuel cell electrode of claim 141. --

-- 144. The fuel cell electrode of claim 114 wherein

said support has a surface area; and,

substantially all of said surface area ionically communicates with an ionomeric membrane.

-- 145. The fuel cell electrode of claim 141 wherein

said support has a surface area; and,

substantially all of said surface area ionically communicates with an ionomeric
membrane.

-- 146. The fuel cell electrode of claim 114 wherein said catalytically effective
load is about 0.01 mg/cm² or less. --

-- 147. The electrode of claim 141 wherein said catalytically effective load is
about 0.01 mg/cm² or less. --

Respectfully submitted,



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ATTORNEY FOR APPLICANT

CERTIFICATE OF MAILING

I hereby certify that this paper, along with any referred to as being attached or enclosed,
is being forwarded to Box PCT, Assistant Commissioner for Patents, Washington, D.C. 20231,
via the United States Postal Service, First Class mail, Postage Prepaid, on 4-3-02, 2000.


Ellen Peacock

**TITLE: A METHOD OF DEPOSITING AN ELECTROCATALYST
AND ELECTRODES FORMED BY SUCH METHOD**

Field of the Invention

5 The application provides a process for depositing a minimal load of an electrocatalyst (preferably comprising platinum) onto a support, preferably a support capable of use as a fuel cell electrode (most preferably carbon cloth), while maximizing the catalytic activity of the catalyst. The application also is directed to products comprising novel electrocatalytic coatings comprising rod-shaped structures

10 **Background of the Invention**

A fuel cell is an electrochemical device in which electrical energy is generated by chemical reaction without altering the basic components of the fuel cell--that is, the electrodes and the electrolyte. Fuel cells combine hydrogen and oxygen without combustion to form water and to produce direct current electric power. The process
15 can be described as electrolysis in reverse. The fuel cell is unique in that it converts chemical energy continuously into electrical energy without an intermediate conversion to heat energy.

Fuel cells have been pursued as a source of power for transportation because of their high energy efficiency (unmatched by heat engine cycles), their potential for fuel
20 flexibility, and their extremely low emissions. Fuel cells have potential for stationary and vehicular power applications. However, the commercial viability of fuel cells for power generation in stationary and transportation applications depends upon solving a number of manufacturing, cost, and durability problems.

One of the most important problems is the cost of the proton exchange catalyst

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for the fuel cell. Some of the most efficient catalysts for low temperature fuel cells are noble metals, such as platinum, which are very expensive. Some have estimated that the total cost of such catalysts is approximately 80% of the total cost of manufacturing a low-temperature fuel cell

5 In a typical process, an amount of a desired noble metal catalyst of from about 0.5-4 mg/cm² is applied to a fuel cell electrode in the form of an ink, or using complex chemical procedures. Unfortunately, such methods require the application of a relatively large load of noble metal catalyst in order to produce a fuel cell electrode with the desired level of electrocatalytic activity, particularly for low temperature
10 applications. The expense of such catalysts makes it imperative to reduce the amount, or loading, of catalyst required for the fuel cell. This requires an efficient method for applying the catalyst.

In recent years, a number of deposition methods, including rolling/spraying, solution casting/hot pressing, and electrochemical catalyzation, have been developed
15 for the production of Pt catalyst layers for proton exchange membrane (PEM) fuel cells. Although thin sputtered Pt coatings deposited on carbon cloth can measurably improve fuel cell performance, this approach generally is not considered to be viable for large area deposition or as a stand alone treatment for applying platinum. Continuing challenges remain in the development of scalable methods for the
20 production of large-area (>300 cm²), high performance (>1A/cm² at 0.6V) fuel cell electrodes with low Pt loadings (<0.3 mg/cm²).

Summary of the Invention

The present invention provides a method for depositing onto a support a vaporizable composition comprising a catalytic component. The method comprises converting the vaporizable composition into a vapor, and depositing the vapor onto the support in an amount sufficient to produce a concentration of the catalytic component adapted to produce a catalytically effective coating on the support. The invention also is directed to electrodes produced by the method, and to electrodes comprising a support comprising a deposit disposed thereon which comprises a catalytically effective load of an electrocatalyst comprising an electrocatalytic active area at least in part comprising rod-shaped structures

Brief Description of the Figures

Figure 1 is a graph depicting the polarization performance of an experimental electrode used as cathode and anode at a cell pressure of 206 85 kPa (30 psig). The experimental electrode was made from a carbon-only ELAT carbon cloth electrode, available from E-TEK, Natick, MA, bearing Pt deposited using electron beam physical vapor deposition (EB-PVD) according to the present invention, as described in Examples III and IV

Figure 2 is a graph depicting the polarization performance at 206 85 kPa (30 psig) cell pressure of a conventional sputtered Pt catalyzed ELAT gas diffusion media experimental electrode used as cathode and anode, as described in Example IV

Figure 3 is a graph depicting the polarization performance at 206.85 kPa (30 psig) cell pressure of a conventional sputtered Pt catalyzed ELAT gas diffusion media experimental electrode used as an anode, as described in Example IV.

Figure 4 is a graph depicting a side-by-side comparison of performance at cell and compensated potentials of a conventional sputtered Pt catalyzed experimental electrode and an inventive EB-PVD Pt catalyzed experimental electrode used as a cathode showing the polarization performance at 206.85 kPa (30 psig) cell pressure, as described in Example IV

Figure 5 is a graph depicting a side-by-side comparison of performance between a conventional sputter deposited Pt electrode and an inventive EB-PVD Pt deposited electrode used as an anode showing the polarization performance at 206.85 kPa (30 psig) cell pressure, as described in Example IV

Figure 6 is a graph depicting a side-by-side comparison of performance at cell and compensated potentials of another conventional sputter deposited Pt electrode and another inventive EB-PVD Pt deposited electrode used as a cathode showing the polarization performance at 206.85 kPa (30 psig) cell pressure, as described in Example IV

Figures 7-9 are field-emission scanning electron microscopy pictures (micrographs or FE-SEMs) of an uncatalyzed ELAT gas diffusion media at various magnifications

Figures 10-20 are FE-SEMs of ELAT gas diffusion media catalyzed using EB-PVD of Pt according to the present invention, as described in Examples III and IV, at various magnifications

Figures 21-26 are FE-SEMs of ELAT gas diffusion media catalyzed using conventional sputter deposition of Pt, as described in Examples III and IV, at various magnifications

Brief Description of the Invention

Vacuum deposition techniques are routinely employed in a variety of applications ranging from metallized layers in the fabrication of semiconductors to barrier coatings for food packaging, hard coatings for cutting tools, and optical thin films. Some of the typical methods employed include chemical vapor deposition, physical vapor or thermal deposition, ion sputtering, and ion beam assisted deposition (IBAD). Because the materials are deposited in a vacuum (typically less than 13.3 mPa, or 1×10^{-4} torr), contamination of the films can be minimized while maintaining good control over film thickness and uniformity. Such techniques, in many cases, lend themselves to deposition of materials over large areas via a reel-to-reel or web coating processes

The present invention uses vacuum deposition techniques, preferably EB-PVD, to deposit a catalyst onto a support. The support for the claimed coating may be any number of materials, preferred materials being suitable for use in electrodes in fuel cells. Such materials include, but are not necessarily limited to proton exchange

membranes (PEMs), carbon cloth, and carbon paper. Preferred supports are carbon supports

Suitable PEMs include, but are not necessarily limited to polymer electrolyte membranes or ionomers, such as NAFION™, available from Dupont, Inc.,

- 5 Wilmington, Delaware, and most preferably a fluoroionomeric membrane comprising a composite of polytetrafluoroethylene with impregnated ion exchange media known as GORE-SELECT®, available from W. L. Gore & Associates, Elkton, Maryland

- Suitable carbon supports include, but are not necessarily limited to, graphite, carbon fiber, and carbon cloth. Suitable commercially available carbon gas diffusion media for use as a support include, but are not necessarily limited to carbon gas diffusion electrodes; iso-molded graphite, carbon bundles, preferably having 6,000 or 12,000 carbon filaments/bundle; reticulated carbon; carbon cloth; and, carbon paper. A preferred carbon support is carbon cloth, preferably a carbon-only ELAT carbon cloth electrode, available from E-TEK, Natick, MA.
- 10

- 15 The support preferably should resist corrosion in an acid environment, offer good electrical conductivity and, for carbon supports, allow fast permeation of oxygen (cathode) and hydrogen (anode), comply with thin layer manufacturing techniques, and contribute little to the weight and cost of the fuel cell assembly

- A catalyst is deposited onto the support, preferably using vacuum deposition techniques. As used herein, the term "catalyst" is defined as a substance that increases the rate of approach to equilibrium of a chemical reaction without being substantially
- 20

consumed in the reaction. A catalyst works by forming chemical bonds to one or more reactants and thereby facilitating their conversion. A catalyst does not affect the reaction equilibrium. A catalyst provides for alternate reaction pathways/mechanisms that offer an overall lower activation energy for the reaction, thus accelerating the rate of turnover

In electrochemical systems the reaction rate (power density/current density) is controlled by controlling temperature and electrocatalysis. Electrocatalysts are substances (metals, metal oxides, non-metals, organometallics, etc.) that can promote the rate of electrochemical reactions, i.e., ionization, deionization, for a given surface area. The electrocatalyst is a substance that accelerates the rate of forward and backward charge transfer reactions for a given redox system (charge transfer reaction) without perturbing chemical equilibrium (thermodynamics is not affected by the presence of a catalyst). An electrocatalyst provides for alternative reaction pathways/mechanisms that offer an overall lower activation energy for the electrochemical reaction, thus accelerating the rate of electrochemical turnover. The rate at which a reaction at an electrode surface proceeds may be limited by the intrinsic kinetics of the heterogeneous process. In non-electrochemical systems, the macroscopically observed reaction rate is the result of a series of elementary processes.

A key difference between an electrocatalyst and other types of catalysts is the ability of the electrocatalyst to manipulate an additional driving force variable: the electric potential. A change in potential of one volt at the surface of the electrocatalyst/electrode can cause a change in reaction rate of eight orders of

magnitude. This change may be equivalent to an increase in temperature of several hundred degrees Celsius for a typical catalytic reaction. (i.e., non-electrochemical reaction). For fuel cell applications heterogeneous electrocatalysts exist as foils, deposited films, individual particles or supported particles. The word "heterogeneous" means that the reactant is normally in a different phase (gas or liquid) than the electrocatalyst (solid).

To describe how a particular surface electrocatalyzes/catalyzes a particular reaction requires a knowledge of three factors: the mechanism of the reaction pathway; the chemisorption energy of the surface species; and, the effective activation energy (energies) of the reaction. Metals with empty "d" orbitals are suitable electrocatalysts because they adsorb H_2 rapidly, with low activation energies of adsorption. Referring to the Periodic Table of the Elements, suitable electrocatalysts include, but are not necessarily limited to: Group IVA metals (Ti, Zr, Hf); Group VA metals (V, Nb, Ta), Group VIA metals (Cr, Mo, W), and, Group VIIA metals (Mn, Tc, Re). These metals appear to adsorb H_2 with high enthalpy of adsorption. Preferred electrocatalysts are metals which adsorb H_2 with lower heats, including but not necessarily limited to Groups VIIIA, B, and C (Fe, Ru, Os, Co, Rh, Ir; Ni, Pd, Pt), preferably Ni, Pd, or Pt, most preferably Pt. The group IB metals (Cu, Ag, Au) have low heats of adsorption, but are not preferred as H_2 adsorption catalysts because they have slow activated chemisorption.

The Group VIII metals, preferred electrocatalysts for use in fuel cell electrodes, are believed to have heats of adsorption in a range which enables the reactant to

chemisorb strongly enough to allow for surface reaction (electrochemical oxidation/reduction by breakdown and discharge of adsorbed species) but not strongly enough to form surface-bonded species. Due to the greater activation energy of chemisorption for oxygen, electrocatalytic reactions which involve surface oxygen

5 require higher temperatures in order to produce satisfactory reaction rates than do reactions which involve surface hydrogen. For example, the most widely used oxygen electrodes for low temperatures are silver and platinum. Summarizing, suitable catalysts for electrochemical applications include, but are not necessarily limited to Pt, Pd, Ru, Rh, Ir, Ag, Au, Os, Re, Cu, Ni, Fe, Cr, Mo, Co, W, Mn, Al, Zn, Sn, with

10 preferred catalysts being Ni, Pd, Pt, most preferably Pt

In order to apply an electrocatalytic coating to the support, the electrocatalyst is heated to vaporization. The heating may be provided using any suitable source, including but not limited to an electron beam, electrical resistance heating, microwave, and laser. In a preferred embodiment, the catalyst is heated using an electron beam

15 In a preferred embodiment, the support is placed in a vacuum chamber provided with a crucible, preferably made of graphite, with a mechanism for directing a high power electron beam onto a solid chunk of the catalyst to produce a catalyst vapor. Where platinum is the catalyst, the catalyst is heated with the electron beam to between about 2300°C-2600°C (4172°F - 4712°F) to form a vapor

20 During the deposition process, the pressure in the vacuum chamber should be pumped down to a pressure sufficient to cause the vapor to condense onto the support

A preferred pressure is about 13.3 mPa (about 10^{-4} torr) or less. As used herein, the term "in a vacuum" is defined to mean a pressure of about 13.3 mPa (10^{-4} torr) or less. The vaporized catalyst preferably should be allowed to deposit or condense onto the support in a vacuum. The temperature in the vacuum may vary; however, the temperature should be low enough not to damage the support, and low enough to permit the catalyst vapor to condense onto the support. Preferably, the temperature should be about 100-200°C or less. The deposition rate preferably should range from about 0.5-10 Å/sec.

The deposition should continue until a catalytically effective amount of the catalyst is deposited onto the support. As used herein, the term "catalytically effective" is defined to mean effective to catalyze the necessary reactions. The term "catalytically effective amount" is defined to mean as small an amount of the catalyst as possible to result in enough active catalyst to catalyze the necessary reactions. Typically, the amount of catalyst deposited to result in a catalytically effective amount should be from about 0.01 to about 0.3 mg/cm², preferably less than about 0.2 mg/cm². The thickness of the coating may be monitored by standard methods, e.g., using the frequency change of a quartz crystal oscillator. The weight of the film may be determined by weighing a known area of the support before and after depositing the film.

The support preferably is used as an electrode in a fuel cell. Preferred fuel cell electrodes are as thin as possible, typically having a thickness between about 0.010-0.175 inches. Where the support is a PEM, the PEM preferably should be treated with

a carbon catalyst support, such as carbon ink, using standard techniques well known in the art. Carbon supports preferably should be wet-proofed

Individual membranes or electrodes may be prepared, or the process may be scaled up for production purposes. Where the support is thermally sensitive, cooling may be required. In the laboratory, cooling may be accomplished by mounting the support on the surface of an aluminum cylinder which is rotated through the ion and coating flux. With this setup, water cooling is no longer necessary because of the sufficiently large thermal mass of the cylinder combined with the fact that the support is no longer continuously exposed to the ion beam and coating flux. This fixture appears to hold promise from a scale-up perspective as large areas of support material can be rolled up on a drum and coated in a reel-to-reel process. Preferably, a scaled up arrangement will be a reel-to-reel arrangement in vacuo. The coating technique described herein is adaptable for use with conventional "web coating" technologies

Upon incorporation into a membrane electrode assembly and into a fuel cell supplied with hydrogen gas under suitable flow conditions, the electrocatalytic coating of the invention exhibits an open circuit voltage of at least about 0.8V, preferably about 1V. The term "open circuit voltage" or "open cell voltage" is defined as the spontaneous potential or voltage present in a fuel cell when no current is allowed to flow. This potential is known as the cell equilibrium potential and its theoretical value can be derived from thermodynamics using the Nernst relationship:

$$E = E^{\circ} + \frac{RT}{nF} \ln \left[\frac{\prod (\text{reactant activity})}{\prod (\text{product activity})} \right] \quad [1]$$

where n is the number of electrons participating in the reaction, F is the Faraday's constant (96,439 coulombs/g-mole electron), R is the universal gas constant, T is the cell temperature and E° is the reversible standard cell potential for the reaction, which is directly related to the maximum electrical work W_e obtainable in a fuel cell operating at constant temperature and pressure and is thermodynamically given by the change in Gibbs free energy (ΔG) of the electrochemical reaction:

$$W_e = \Delta G^{\circ} = -nFE^{\circ} \quad [2]$$

For the overall cell reaction, the open circuit potential increases with an increase in the activity of reactants and a decrease in the activity of products. Changes in cell temperature and pressure also influence the reversible cell potential. Practically, the open circuit voltage is the maximum voltage attainable during a fuel cell polarization or I/V curve, and corresponds to the cell potential at which the drawn net cell current is zero.

For example, after appropriate equilibration time, a PEM fuel cell will observe an open circuit voltage of from about 0.8 V and about 1 V versus a reference standard

- hydrogen electrode when operating: (a) at a temperature of from about 50° C to about 130° C; (b) with hydrogen and air as reactants; (c) humidified at a temperature of from about 50° C to about 140° C; (d) with relative humidities of from about 0 to about 100 %; (e) with pressures of from about 0 to about 100 psig; and, (f) with flows
- 5 large enough to assure complete irrigation of the electrocatalyst phase throughout the electrode.

- The vacuum deposition techniques of the present invention are capable of forming large-area ($>300 \text{ cm}^2$), high performance fuel cell electrodes with low Pt loadings ($<0.3 \text{ mg/cm}^2$, preferably about 0.1 mg/cm^2) which are capable at a cell
- 10 potential of about 0.6 V of producing a power output of well over 400 mA cm^{-2} , preferably over about 800 mA cm^{-2} , most preferably about 1000 mA cm^{-2} , under the following conditions: in a single cell fuel cell fixture, with appropriate gas distribution manifolds and appropriate gasketing; using ELAT as gas diffusion material; with appropriate cell compression (from about 5.65 to about 33.89 N m/bolt, or about 50 to
- 15 about 300 lb in/bolt compression torque), at cell operating conditions which typically include water saturation of the anode and (H_2) reactant feed at humidification temperatures of from about 40 to about 90°C, cell temperatures of about 40 to about 80°C, volumetric flowrate reactant feeds of about 1.2 -2 and about 2-5 times the stoichiometric value, for H_2 and air, respectively, and cell pressure set from about 0 to
- 20 about 413.7 kPa gauge (1 and about 60 psig) for the anode (H_2 electrode) and cathode (air electrode)

Tafel analysis on experimental cathodes (described in Example IV)

demonstrates about a five-fold difference in oxygen reduction exchange current density between the vapor deposition techniques of the present invention and conventional sputtered electrodes ($i_{0,PVD}/i_{0,sputt} \sim 4.89$). The difference suggests that vapor deposited cathodes, such as the EB-PVD Pt deposited cathodes formed in Examples III and IV, have a substantially larger electrocatalytic active area or "three phase boundary" (TPB) than conventional sputtered Pt cathodes. This electrochemical conclusion was confirmed by field-emission scanning electron microscopy pictures (micrographs or FE-SEMs). FE-SEMs showed the presence of a microstructure in the inventive vapor deposited electrodes with readily recognizable Pt particles and the presence of "rod-shaped" structures 10, which become visible beginning at about x10k magnification, as shown in Figs 14-15 and 17-22. These rod-shaped particles were not observed in the sputtered sample, as shown in Figs 23-28.

For purposes of the present application, the term "rod-shaped" is defined to mean substantially cylindrical shaped structures having a diameter 10a, as shown in Fig. 17, and a length 10b, as shown in Fig. 17. The rod-shaped structures shown in Figs. 12-13 and 15-20 have (a) a diameter 10a (Fig. 17) of from about 40-about 60 nm, typically about 60 nm, and (b) a length which is difficult to verify, but appears to vary

Electrodes made according to the present invention may be used in fuel cells having many different constructions known to those skilled in the art. The invention will be better understood with reference to the following examples, which are for illustrative purposes only and should not be construed as limiting the invention, which

is defined by the claims

EXAMPLE I

Using a vacuum chamber 2 m long and 1.5 m in diameter, candidate coatings were first deposited on glass slides and small coupons of representative membrane and electrode material, and subjected to compositional and microstructural analysis. Next, a series of larger-area electrode materials were coated and evaluated using a small home-built test cell, described below

After a final down-selection, a limited number of full scale 150 cm² electrodes were fabricated and tested. Special sample fixtures, described in more detail in Example II, were developed to allow for the coating of carbon cloth electrodes over areas as large as 300 cm². Samples up to 250 cm² were coated using a planetary gear arrangement. The samples were asynchronously rotated through an electron beam-physical vapor deposition (EB-PVD) coating flux to ensure uniform deposition of the Pt over the entire electrode surface.

Carbon cloth and carbon paper materials, both plain and wet-proofed (i.e. coated with TEFLON[®]), were coated with 0.01, 0.05, and 0.10 mg/cm² of Pt. In addition, wet-proofed samples treated with a layer of carbon-only ELAT were procured from E-TEK for Pt coating in a similar manner

A comparison of the thicknesses, morphologies, and Pt distributions of selected fuel cell electrode materials was performed using scanning electron microscopy (SEM)

and transmission electron microscopy. The objective of such measurements was to determine the effect of electrode structure on the resulting efficiency of the fuel cell.

Performance analysis of catalyst coated electrode materials was undertaken using a small "home-built" test cell. The simple test cell consisted of two 6.9 cm stainless steel flanges used as collector plates with single air/hydrogen inlets and pairs of 100-mesh stainless steel screens mounted on each side of the electrode to provide a degree of gas diffusion. The cell active area was approximately 64 cm² and the same electrode material was used for both the anode and the cathode. The system was pressurized with humidified hydrogen and compressed air at 96.53 kPa (14 psig) and a flow rate of ~0.5 liters per minute. Current-voltage tests were conducted at ambient temperature at each outlet.

In all tests, the EB-PVD Pt-coated ELAT material repeatedly demonstrated superior behavior compared to a higher loaded control material, namely E-TEK platinum over VULCAN XC-72 ELAT solid polymer electrolyte electrode (4 mg/cm²). Measurable improvements in efficiency were observed for the carbon cloth with increasing Pt loading. It was also possible to further reduce the Pt loading of the EB-PVD coated carbon-only material on the anode side to as low as 0.01 mg/cm² with minimal reduction in performance.

EXAMPLE II

Fabrication and testing of three full scale 150 cm² electrodes was performed based on the results of the screening tests with the small test fixture.

The electrodes prepared for testing are summarized in Table 2.

TABLE 2

Sample I.D	Membrane/Electrode Material	Deposition Method	Pt Loading (mg/cm ²) (Anode/Cathode)
1	20 μ m GORE SELECT [®] /C-only ELAT	EB-PVD Pt	0.10/0.01
2	50 μ m GORE SELECT [®] /C-only ELAT	EB-PVD Pt	0.05/0.05
3	20 μ m GORE SELECT [®] /C paper	Sputtered Pt	0.10/0.10

In order to effectively evaluate the full-scale electrodes, a Scribner Associates Model 890 load system was leased for use with a test fixture. Basically, the test fixture consisted of the chosen membrane sandwiched by the chosen electrodes surrounded by graphite plates having flow channels to allow the passage of hydrogen and oxygen gas into contact with the electrodes. A metal plate sandwiched the assembly on each side. The metal plates had suitable holes drilled for introducing the hydrogen and oxygen gas, and electrical leads collected current and connected each plate to the load unit. The 1 kW, 125 amp Scribner load unit recorded all performance data from the cell while controlling the temperatures of the cell and feed gases, ensuring consistent, repeatable results. The comparison test fixture was rated at more than 100 watts.

depending on the configuration and operational mode. The modular design of the cell allowed for many different possible configurations and use of different material thicknesses.

Particular attention was paid to the gas handling system in assembling the test cell. All of the tubing and connectors were made of a 316 stainless steel and TEFLON (where electrical isolation was needed) in an effort to limit transport of metal cations into the cell. The gases were passed through a pair of Perma Pure Inc. NAFION-based humidifiers and then carried to the cell via stainless tubing wrapped in heater tape to maintain proper temperature. Next, each gas was directed into 3-branch manifolds for the gas inlets and outlet. Exhaust gases were passed through a pair of flowmeters to measure the amount of excess fuel and air flow. Flowmeters were not installed on the upstream side as they contain a significant amount of aluminum parts which may contaminate the gases and hinder cell performance. A stainless steel reservoir with a built in heater was used to heat the cell and was controlled by the Scribner load unit. A plastic submersible chemical pump circulated deionized water in a closed circuit composed of TEFLON tubing through the cell and humidifiers and back to the container. No active cooling of the cell was needed.

Performance tests typically were conducted at a temperature of 60°C, 30 psi humidified gasses, 3.5 time Stoichiometric Ratio (SR) or less on the air side, and 2 SR or less on the reactant side. The first objective was to match the performance curves for the electrode of the present invention with the control, comprising an electrode from a Gore PRIMEA® membrane electrode assembly, available commercially from

W L. Gore & Associates, Inc., under similar test conditions. After assembly, the cell was conditioned for several hours at low current. Once the performance stabilized, current voltage data was acquired starting at high currents and slowly ramping down.

Once the performance curve of the test membrane/electrode assembly had been matched with the performance curves of the controls, testing was performed. The cell was first conditioned for eight hours at a low current setting with humidified gasses at 30 psi. The highest current density achieved using the 100nm/10nm EB-PVD Pt-coated ELAT with the 20 μm membrane was 732 mA/cm² at 358 V. In general, the overall power output of EB-PVD deposited electrode was 10-50% less than the output of the control. However, it is important to point out that this performance was achieved with less than 20% of the total Pt loading of the baseline material.

The foregoing tests demonstrate successful use of EB-PVD in the fabrication of 150 cm² membrane electrode assemblies with total Pt loadings as low as 0.11 mg/cm².

EXAMPLE III

Experiments were performed to characterize the electrochemical (fuel cell performance) and morphological properties of experimental electrodes prepared by Pt EV-PVD and magnetron sputtering of ELAT® gas diffusion media. MEAs prepared with PVD electrodes (cathodes or anodes) yielded superior polarization performance compared to the sputtered half cells.

Electrode preparation Vacuum vaporization-based catalyzed electrodes were prepared using (a) electron-beam physical vapor deposition (EB-PVD) according to the present invention, and (b) conventional magnetron sputtering of Pt. In each case, the Pt was deposited onto double-sided ELAT commercial carbon-cloth gas diffusion media. The catalyzation took place onto the "active side" of the diffusor, i.e., on the side normally in contact with electrocatalyst layers

For EV-PVD, a catalyst deposition rate of 1 \AA/sec was chosen. The chamber base pressure was about 13.3 mPa (10^{-5} torr). The Pt source was 99.95% purity.

For magnetron sputtering, a 15.24 cm (6 in) diameter magnetron sputtering unit was used to sputter Pt onto the substrate at a rate of about 2 to about 3 \AA/sec . The chamber base pressure was about 1.33 mPa (10^{-4} torr). The Pt target was a foil with a purity 99.99%.

Electrodes at a loading level of $0.1 \text{ mg Pt cm}^{-2}$ were prepared using both techniques and compared. Energy dispersive spectroscopy (EDS) x-ray analysis detected only Pt as the vaporized phase using either technique. The catalyst layers formed using either technique had an average thickness of about 500 \AA .

The Pt-catalyst electrodes were incorporated into experimental MEA's using methods known in the art. In order to solely characterize the performance of the vacuum coated electrode, e.g., as cathodes, MEA's were prepared using a Gore PRIMEA[®] membrane electrode assembly as an anode, and vice versa when the vacuum coated electrode was characterized as the anode half cell. The Gore PRIMEA[®]

membrane electrode assembly presented a loading of $0.1 \text{ mg Pt cm}^{-2}$ and the experimental MEA's used a $30 \text{ }\mu\text{m}$ GORE SELECT* (950EW) perfluorinated membrane to form a membrane electrode assembly in all cases

EXAMPLE IV

5 *Fuel Cell and Tafel Performance Tests:* To electrochemically characterize the performance of the experimental electrodes as cathodes and anodes, H_2 /air fuel cell testing analysis was performed. The MEAs containing electrode active areas of 25 cm^2 and $30 \text{ }\mu\text{m}$ GORE SELECT* membranes were mounted in standard fuel cell reactor fixtures using ELAT gas diffusion media for the reference half cell and were clamped
10 to standard compression levels. The fuel cell test was conducted using a fuel cell station commercially available from Globetech, Inc., Bryant, TX. For the pressurized experiments, a 103.43/103.43 kPa and 206.85/206.85 kPa (15/15 psig and 30/30 psig) gauge anode and cathode, respectively, the cell temperature was set at about 80°C with anode and cathode feeds humidified at about $60\text{--}70^\circ\text{C}$ and 85°C ; and, flowrates
15 set at 2/3 5 times the stoichiometric value for H_2 and air, respectively. In some tests, a constant flow of 500-1000 standard cm^3/min was used for the H_2 and air, respectively. For the atmospheric pressure runs, the cell temperature and reactant humidification was set at about 60°C . The performance was evaluated at different times on stream (TOS)

20 *Fuel Cell Performance Analysis:* Fig. 1 shows the polarization performance at 206.85 (30 psig) cell pressure of a Pt EB-PVD catalyzed ELAT gas diffusion media

experimental electrode used as a cathode and anode. The MEA used was a Gore PRIMEA® membrane electrode assembly (anode or cathode). Figs. 2 and 3 are the equivalent graphs (at different cell pressures) for the Pt-sputtered experimental electrode used as cathode and anode. Polarization performance from these graphs suggests that the Pt evaporated electrode displayed superior performance compared to the sputtered electrode for both cathode and anode operation.

Figures 4 and 5 show a side-by-side comparison of performance between both vacuum catalyzed technologies. When used as a cathode, the inventive PVD catalyzed electrode showed improved performance throughout the entire polarization curve, i.e., OCV, activation region, ohmic region and mass transport region, compared with the sputtering catalyzed electrode (Fig. 4). For example, at 0.6V, the MEA containing the PVD half cell operating as cathode yielded about 400 mA cm^{-2} with an OCV of 0.889 V against $60\text{--}100 \text{ mA cm}^{-2}$ and OCV of 0.779–0.810 V for the sputtered system (i.e., 4 times lower performance). The compensated (IR-free) performance for the sputtered system followed the curve for the total cell potential indicating that the controlling electrode was the cathode half cell.

Fig. 5 shows the same analysis, but with the vacuum vaporized electrode used as anode. Here, although the OCV and the catalyst regions of the polarization curves were comparable for both systems (as expected due to the reference cathode operating as cathode in both cases), the IR region and the mass transport region for the MEA containing the sputtered electrode demonstrated substantially lower performance, i.e., larger slope, (larger membrane resistance and anode linear polarization losses) and

more pronounced mass transport effects. For example, at 0.6 V cell potential, the MEA containing the sputtered anode yielded between 300 and 400 mA cm⁻² while the PVD anode-containing MEA yielded almost 1000 mA cm⁻². The difference in performance observed in this case (experimental electrode used as anode) was mostly

5 due to anode polarization differences: at 0.6 V the sputtered anode suffered about 240 mV polarization loss against 92 mV polarization loss for the EB-PVD cathode.

Tafel Analysis: In order to rationalize the difference in performance of electrodes made using EB-PVD versus sputtering, the electrocatalytic activity/activation polarization performance of the electrode was probed using a Tafel

10 analysis. Briefly, a fuel cell polarization curve can be described using the semi-empirical equation:

$$E = E_o - b \log i - iR - m e^m$$

where the first negative term ($-b \log i$) indicates the cathode activation loss (electrocatalyst/electrodics, i.e., resistance to charge transfer), the second negative

15 term ($-iR$) addresses the ohmic losses due to membrane resistance, contact potential and anode linear polarization losses, and the third negative term ($-m e^m$) addresses mass transport polarization losses. During a Tafel analysis, the ohmic and mass transport losses are normally eliminated and electrocatalytic parameters are measured by curve fitting the data to the following expression:

20 $E_c = E + iR \approx E_o - b \log i$

where the compensated (iR -free) cell potential is used to eliminate any ohmic loss that could be present in the catalyst region of the polarization curve. The Tafel slope, b and the parameter E_o (which is related to the exchange current density i_o , and, thus related to the polarizability of the interface due to its dependence with the intrinsic electrocatalytic activity and the length of three phase boundary, TPB, i.e., number of electrocatalytic active sites or electrochemically active surface area) were then evaluated for the evaporated and sputtered vacuum coated electrodes used as a cathode (controlling half cell). The experimental Tafel curve is shown in Fig. 6.

Tafel analysis suggested that, although the Tafel slope for the evaporated electrode was larger than the sputtered electrode, the PVD cathode provided a substantially larger electrocatalytic active area (larger TPB) than the sputtered cathode, as found comparing the E_a values for both electrodes 1.145V (PVD) versus 0.853 V (sputtering). The superior polarization performance of the PVD electrode compared with the sputtered electrode can then be explained on the basis that the exchange current density i_o for oxygen reduction in the evaporated electrodes was about 5 times higher than that in the sputtered electrode due to the larger electrochemically active area.

Although the foregoing argument is directly valid for the catalyst region of the polarization curve, the difference in performance observed at the ohmic and mass transport regions of the curve is only indirectly related to the reduced electrocatalytic active area. Factors which would directly relate to the difference in performance at the ohmic and mass transport regions of the curve would be, e.g., reduced hydration of

membrane (due to lower current densities) or flooding. These factors, nevertheless, are directly related to current density, which is directly related to the extent of electrocatalytic area.

FE-SEM Analysis: In order to characterize the microstructure of the vacuum catalyzed electrodes, field-emission SEM was performed. FE-SEM micrographs for the uncatalyzed ELAT gas diffusion media were compared to FE-SEM micrographs for the Pt EB-PVD catalyzed ELAT diffuser and Pt sputtered catalyzed diffuser. Magnifications from x5k up to x50k were used. Pictures with x25k and x50k magnification showed most of the differences in structure.

Significant differences on the morphology of the Pt catalyst coating were observed between the EB-PVD and magnetron sputtering coating technologies. On the sputtered sample, the Pt particles were in the form of aggregates (Figs. 23-28), and in some cases the particles appeared to coalesce and form larger "fused" particles with a longitudinal dimension (18c, 18d, Fig. 25) of from about 400 to about 1000 nm. In these "fused" particles (18c, 18d, Fig. 25), the outer surface of individual particles was no longer visible (18, 18a, and 18b in Figs. 26 and 27).

On the EB-PVD catalyzed sample, the Pt particles were in the form of aggregates and in some cases the particles (12, Fig. 17) appeared to coalesce and form patches (14, Fig. 17). But the outer surface of individual Pt particles (12, Fig. 17) was readily recognizable in the coalesced patches as compared to that of the coalesced particles in the Pt sputtered sample (18, 18a, 18b, Figs. 26 and 27). In addition, a

good amount of rod-like Pt particles 10 (Figs. 14, 15, and 17-22) were observed on the EB-PVD catalyzed sample. These rod-like particles were not observed in the sputtered sample.

Persons of ordinary skill in the art will recognize that many modifications may
5 be made to the present invention without departing from the spirit and scope of the present invention. The embodiments described herein are meant to be illustrative only and should not be taken as limiting the invention, which is defined in the following claims

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We claim:

1 1. A method for depositing onto a support one or more catalytic components,
2 said method comprising:
3 providing one or more vaporizable catalytic components;
4 converting said one or more vaporizable catalytic components into a vapor; and
5 depositing said vapor onto said support in an amount sufficient to produce a
6 concentration of said one or more catalytic components adapted to
7 produce a catalytically effective coating consisting essentially of said
8 one or more catalytic components on said support.

1 2. The method of claim 1 wherein at least said depositing occurs in a
2 vacuum.

1 3. The method of claim 1 or 2 wherein said support is a carbon catalyst
2 support.

1 4. The method of claim 3 wherein said carbon catalyst support comprises a
2 material selected from the group consisting of graphite, a carbon filament bundle,

3 reticulated carbon, carbon cloth, and carbon mesh.

1 5. The method of any of claims 1-4 wherein said support comprises a
2 membrane comprising a composite of polytetrafluoroethylene comprising impregnated
3 ion exchange media, said composite comprising a thickness of about 1 μm .

1 6. The method of any of claims 1-5 wherein said one or more catalytic
2 components comprises one or more noble metals.

1 7. The method of any of claims 1-6 wherein said one or more catalytic
2 components comprises one or more metals selected from the group consisting of
3 platinum, gold, silver, palladium, ruthenium, rhodium, iridium.

1 8. The method of any of claims 1-7 wherein said concentration comprises less
2 than about 0.3 mg/cm^2 .

1 9. The method of any of claims 1-7 wherein said concentration comprises less
2 than about 0.2 mg/cm^2 .

1 10. The method of any of claims 1-7 wherein said concentration comprises
2 from about 0.01 to about 0.2 mg/cm².

1 11. The method of any of claims 1-10 wherein said one or more catalytic
2 components comprise platinum.

1 12. The method of any of claims 1-11 wherein said support is a coating on a
2 carbon cloth, wherein said coating is selected from the group consisting of carbon, a
3 wet proofing material, and a combination thereof.

1 13. The method of claim 12 wherein said wet proofing material is polytetra-
2 fluoroethylene.

1 14. The method of any of claims 1-13 further comprising
2 providing a solid polymer electrolyte membrane; and
3 disposing said support in ionic communication with said solid polymer
4 electrolyte membrane.

1 15. The method of any of claims 1-14 wherein
2 said solid polymer electrolyte membrane has a first side and a second side
3 opposite said first side, and
4 said method further comprises disposing said support on each of said first side
5 and said second side to produce a membrane electrode assembly.

1 16. The method of any of claims 1-15 wherein said converting is thermally
2 converting.

1 17. The method of any of claims 1-5 wherein said one or more catalytic
2 components are metallic.

1 18. An electrode produced by a process comprising:
2 providing one or more vaporizable catalytic components;
3 converting said one or more vaporizable catalytic components into a vapor; and
4 depositing said vapor onto a support in an amount sufficient to produce a

concentration of said one or more catalytic components adapted to produce a catalytically effective coating consisting essentially of said one or more catalytic components on said support.

1 19. The electrode of claim 18 wherein said support is a carbon catalyst support
2 comprising a material selected from the group consisting of graphite, a carbon filament
3 bundle, reticulated carbon, carbon cloth, and carbon mesh.

1 20. The electrode of claim 19 wherein said carbon catalyst support
2 comprises a material selected from the group consisting of a carbon cloth and a coating
3 on a carbon cloth selected from the group consisting of carbon, a wet proofing
4 material, and a combination thereof.

21. The electrode of claims 18-20 wherein said support comprises a
membrane comprising a composite of polytetrafluoroethylene comprising impregnated
ion exchange media, said composite comprising a thickness of about 1 μm .

1 22. The electrode of any of claims 18-21 wherein said one or more vaporizable
2 catalytic components comprises one or more noble metals.

1 23. The electrode of claim 22 wherein said one or more vaporizable
2 catalytic components comprises one or more metals selected from the group consisting
3 of platinum, gold, silver, palladium, ruthenium, rhodium, iridium.

1 24. The electrode of any of claims 18-23 wherein said one or more
2 vaporizable catalytic components comprises platinum.

1 25. The electrode of any of claims 18-24 wherein said support comprises a
2 coating on a carbon cloth wherein said coating is selected from the group consisting of
3 carbon, a wet proofing material, and a combination thereof.

1 26. The electrode of claim 25 wherein said wet proofing material is
2 polytetra-fluoroethylene.

1 27. The method of any of claims 18-26 wherein said converting is thermally
2 converting.

1 28. The method of any of claims 18-21, 25, and 26 wherein said one or
2 more catalytic components are metallic.

1 29. An electrode comprising a support having disposed thereon a vapor
2 deposited electrocatalytic coating consisting essentially of one or more electrocatalysts,
3 wherein said one or more electrocatalysts are present in an amount of about 0.3
4 mg/cm² or less.

1 30. The electrode of claim 29 wherein said vapor deposited electrocatalytic
2 coating is deposited in a vacuum by electron-beam physical vapor deposition.

1 31. The electrode of claims 29 and 30 wherein, at a cell potential of about 0.6
2 V, an MEA containing said electrode half cell operating as a cathode yields about 800
3 mA cm⁻² or greater.

1 32. The electrode of claims 29-31 wherein said electrode comprises an
2 electrocatalytic active area of about 300 cm² or greater.

1 33. The electrode of claims 29-32 wherein said one or more catalytic
2 components comprises platinum.

1 34. The electrode of claims 29-33 wherein said support comprises a
2 membrane comprising a composite of polytetrafluoroethylene comprising impregnated
3 ion exchange media, said composite comprising a thickness of about 1 μm .

1 35. The electrode of claims 29-34 wherein said converting is thermally
2 converting.

1 36. An electrode comprising a support comprising a deposit disposed
2 thereon, said deposit comprising a catalytically effective load of an electrocatalyst
3 comprising an electrocatalytic active area at least in part comprising rod-shaped
4 structures.

1 37. The electrode of claim 36 wherein said rod-like structures are visible at
2 a magnification of at least about $\times 10\text{k}$.

1 38. The electrode of claims 36 and 37 wherein said deposit further
2 comprises particles of said electrocatalyst comprising an outer surface, wherein said
3 electrocatalytic active area comprises a majority of said outer surface of said particles.

1 39. The electrode of claims 36-38 wherein said support has a surface area, and
2 said deposit covers about 300 cm² or more of said surface area.

1 40. The electrode of claims 36-39 wherein said catalyst comprises platinum.

1 41. The electrode of claims 36-40 wherein, at a cell potential of about 0.6
2 V, an MEA containing said electrode as a half cell operating as a cathode yields a
3 power output of about 400 mA cm⁻² or greater.

1 42. The electrode of claims 36-40 wherein, at a cell potential of about 0.6
2 V, an MEA containing said electrode as a half cell operating as a cathode yields a
3 power output of about 800 mA cm⁻² or greater.

1 43. The electrode of claims 36-40 wherein, at a cell potential of about 0.6

- 2 V, an MEA containing said electrode as a half cell operating as a cathode yields a
3 power output of about 1000 mA cm^{-2} or greater.

- 1 44. The electrode of claims 36-43 wherein said support comprises a
2 membrane comprising a composite of polytetrafluoroethylene comprising impregnated
3 ion exchange media, said composite comprising a thickness of about $1 \mu\text{m}$.

- 1 45. A membrane electrode assembly comprising the support of any of claims
2 18-44.

- 1 46. The electrode of any of claims 18-44 wherein
2 said support has a surface area; and,
3 substantially all of said surface area ionically communicates with an ionomeric
4 membrane.

- 1 47. The electrode of claim 46 wherein said surface area is 300 cm^2 or
2 greater.

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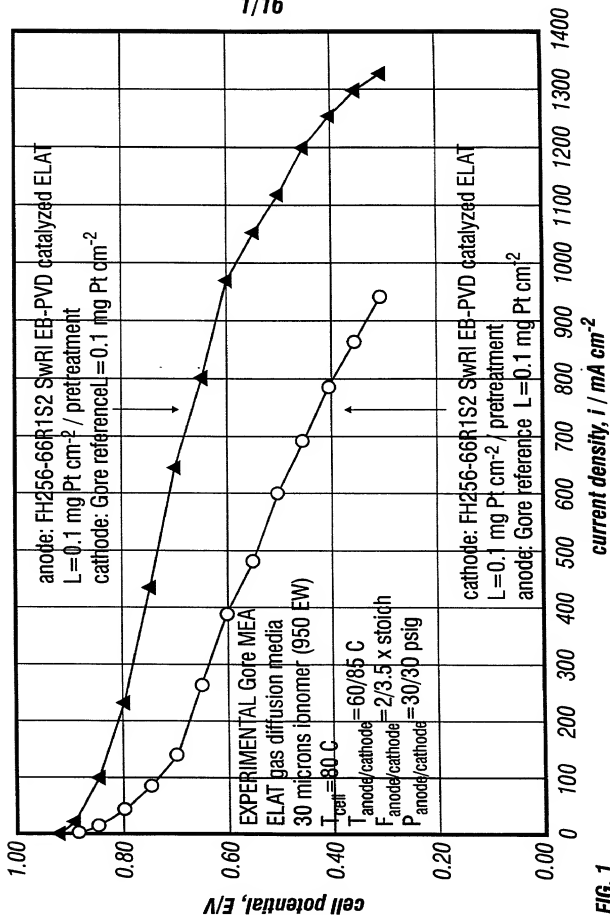


FIG. 1

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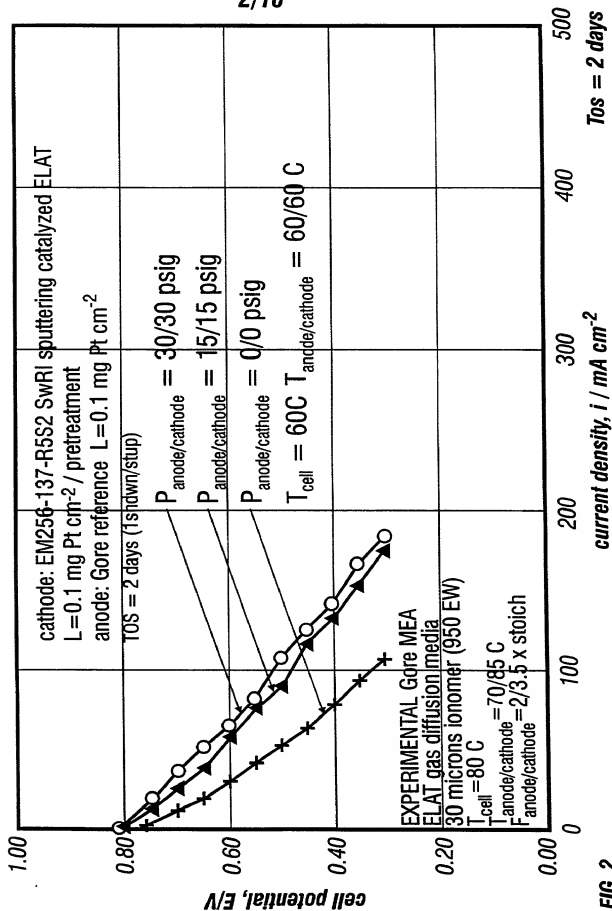


FIG. 2

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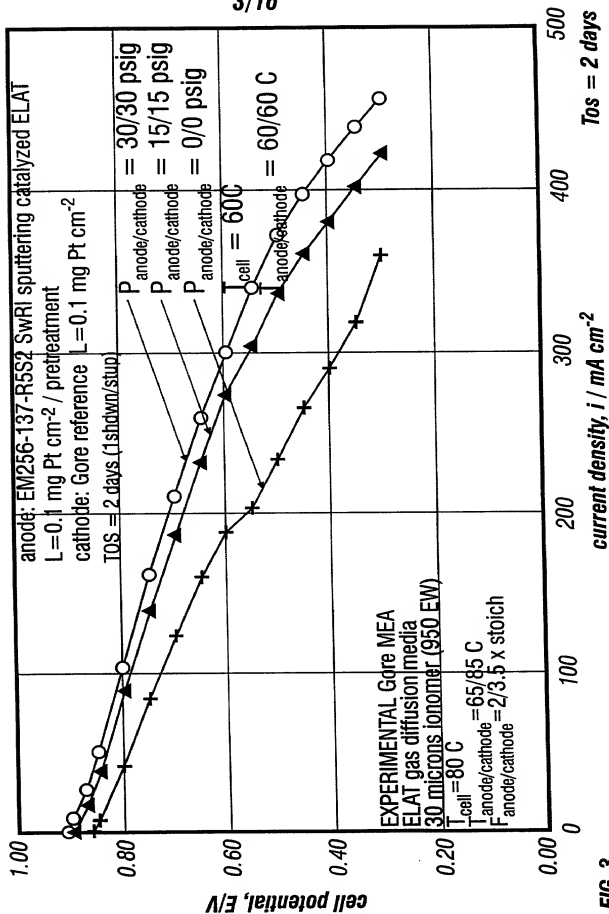


FIG. 3

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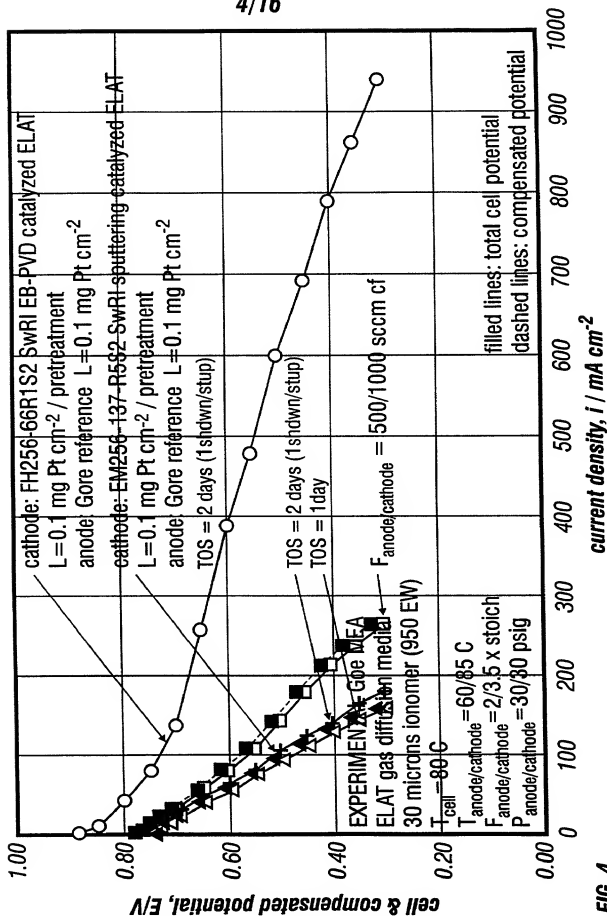


FIG. 4

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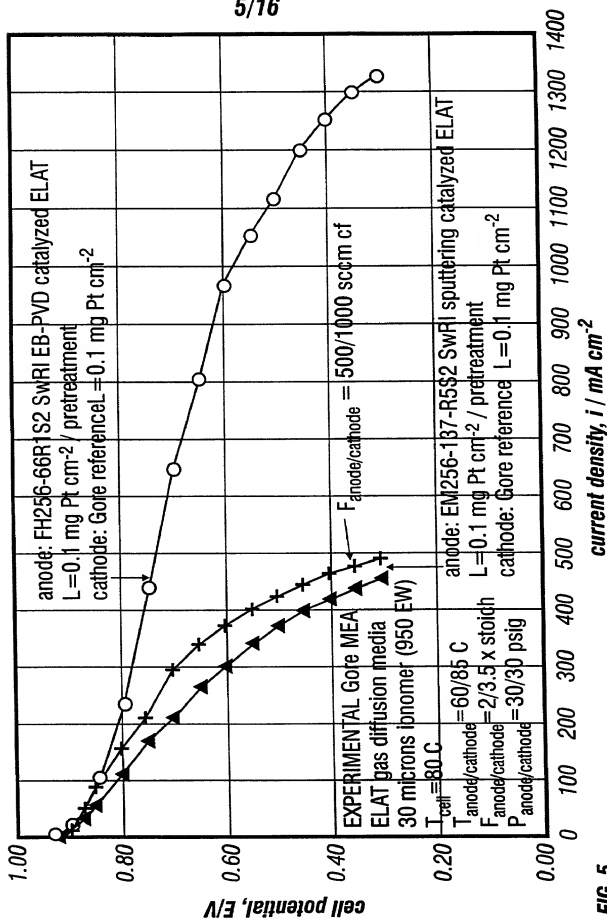
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FIG. 5

ATTACHED SHEET

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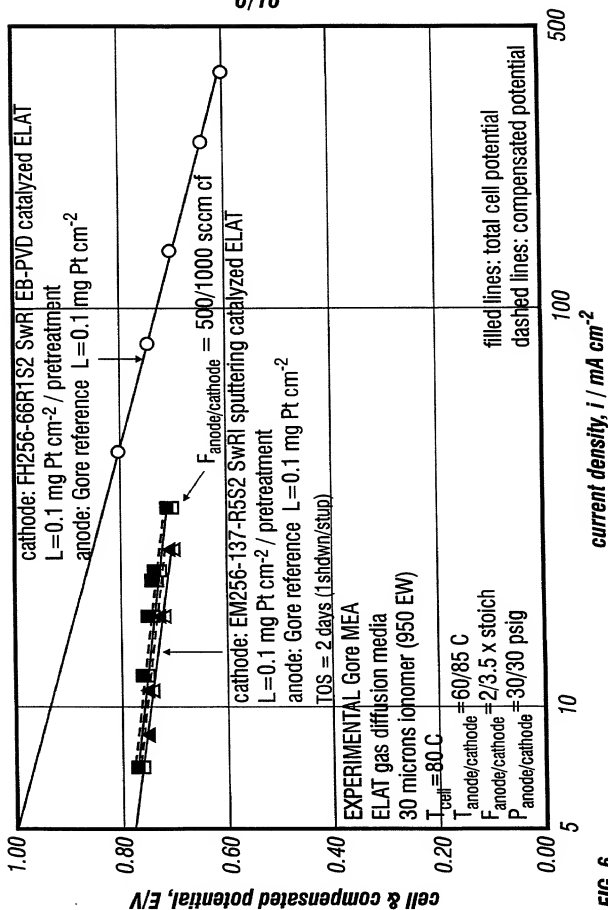


FIG. 6

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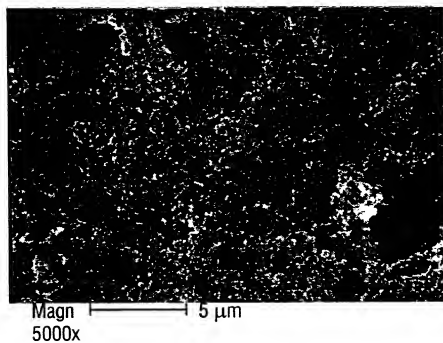


FIG. 7

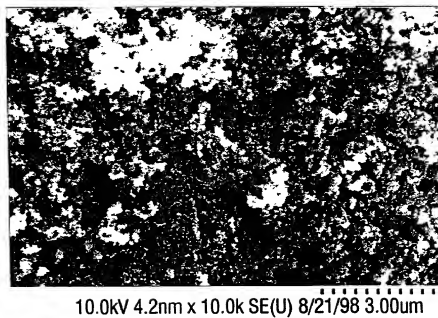
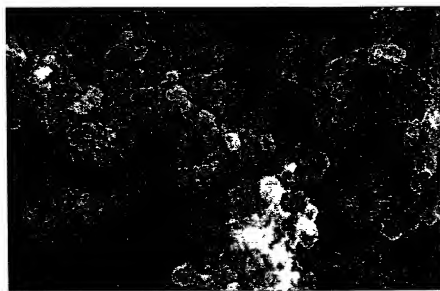


FIG. 8

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10.0kV 4.2nm x 50.0k SE(U) 8/21/98 600nm

FIG. 9



ebpvd 10.0kV 5.0nm x 5.00k SE(U) 8/21/98 6.00um

FIG. 10

ARMED SHEET

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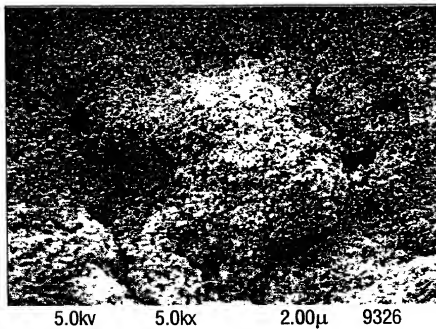


FIG. 11

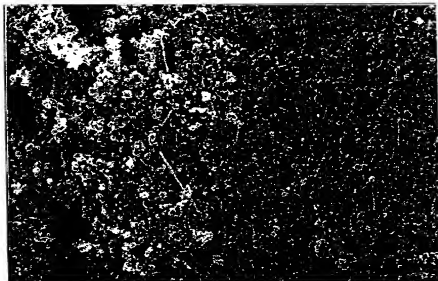


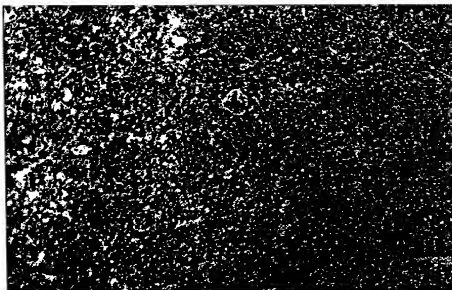
FIG. 12

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ebpdv10.0kV 5.0nm x 10.0k SE(U) 8/21/98 3.00um

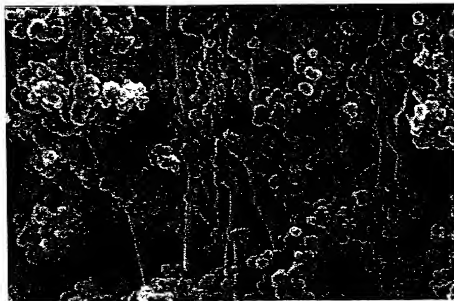
FIG. 13



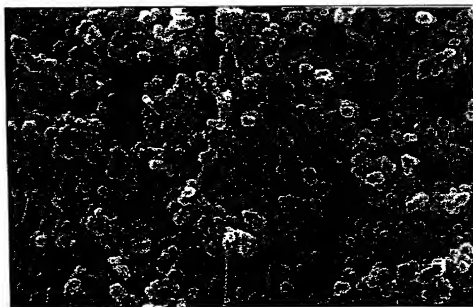
10.0kV 5.0nm x 5.00k SE(U) 8/21/98 6.00um

FIG. 14

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10.0kV 5.0nm x 25.0k SE(U) 8/21/98 1.20μm

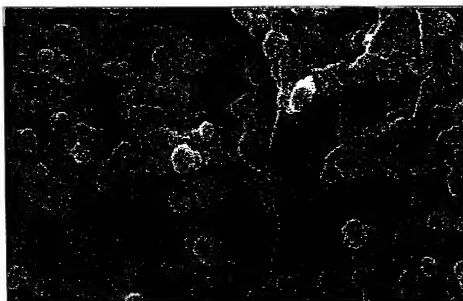
FIG. 15

10.0kV 5.0nm x 25.0k SE(U) 8/21/98 1.20μm

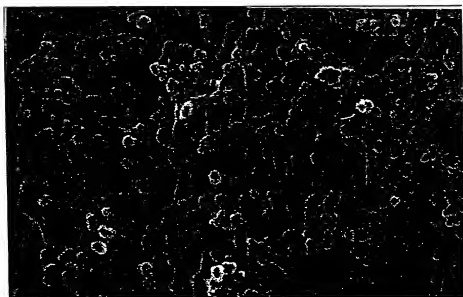
FIG. 16**AMENDED SHEET**

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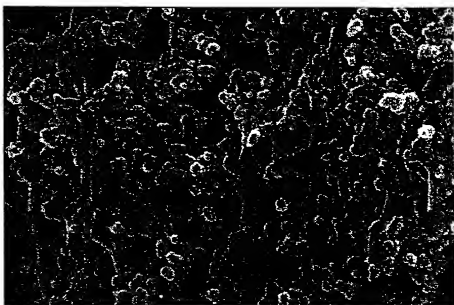


ebpvd 10.0kV 5.0nm x 50.0k SE(U) 8/21/98 600nm

FIG. 17

10.0kV 5.0nm x 25.0k SE(U) 8/21/98 1.20um

FIG. 18



ebpvd 10.0kV 5.0nm x 25.0k SE(U) 8/21/98 1.20um

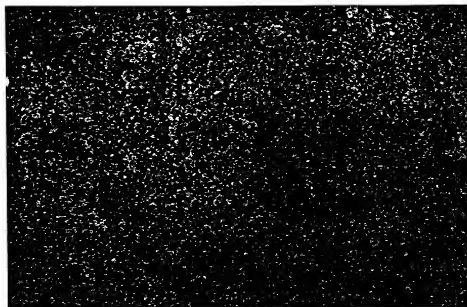
FIG. 19



ebpvd 10.0kV 5.0nm x 50.0k SE(U) 8/21/98 600nm

FIG. 20

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sputter 10.0kV 4.2nm x 5.00k SE(U) 8/21/98 6.00um

FIG. 21

sputter 10.0kV 4.2nm x 50.0k SE(U) 8/21/98 6.00nm

FIG. 22



sputter 10.0kV 4.2nm x 50.0k SE(U) 8/21/98 600nm

FIG. 23

sputter 10.0kV 4.2nm x 25.0k SE(U) 8/21/98 1.20um

FIG. 24



sputter 10.0kV 4.2nm x 50.0k SE(U) 8/21/98 600nm

FIG. 25



sputter 10.0kV 4.2nm x 25.0k SE(U) 8/21/98 1.20um

FIG. 26

SENT BY:

; 9-15-00 ;12:40PM ; LEGAL DEPARTMENT+

713 223 1476;# 2

DECLARATION AND POWER OF ATTORNEY FOR PATENT APPLICATION

As the below named inventor, we hereby declare that:

Our residence, post office address and citizenship are as stated below under our names.

We believe that we are the original, first and joint inventors of the subject matter which is claimed and for which a patent is sought on the invention entitled **METHOD OF DEPOSITING AND ELECTROCATALYST AND ELECTRODES FORMED BY SUCH METHODS**, Attorney Docket No. GORE/M/192/US, the specification of which:

— is attached hereto.

X was filed on April 3, 2000, as Application Serial No. 09/509,849, including claims as amended.

We hereby state that we have reviewed and understand the contents of the above-identified specification, including the claims, as amended by any amendment referred to above.

We acknowledge the duty to disclose all information known to me to be material to the patentability of this application in accordance with Title 37, Code of Federal Regulations, §1.56.

We hereby claim foreign priority benefits under Title 35, United States Code, §119 of any foreign application(s) for patent or inventor's certificate listed below and have also identified below any foreign application for patent or inventor's certificate having a filing date before that of the application on which priority is claimed:

PRIOR FOREIGN APPLICATION(S)

NUMBER	COUNTRY	DAY/MONTH/YEAR FILED	PRIORITY CLAIMED
NO			

We hereby claim the benefit under Title 35, United States Code, §120 of any United States application(s) listed below and, insofar as the subject matter of each of the claims of this application is not disclosed in the prior United States application in the manner provided by the first paragraph of Title 35, United States Code, §112, we acknowledge the duty to disclose material information as defined in Title 37, Code of Federal Regulations, §1.56(a), regarding events which occurred between the filing date of the prior application and the national or PCT international filing date of this application:

(Application Serial No.)	(Filing Date)	(Status)
08/927,739	September 11, 1997	Pending
09/135,257	August 17, 1998	Pending

We hereby appoint the following attorneys and/or agents to prosecute this application and to transact all business in the Patent and Trademark Office connected therewith:

Paula D. Morris, Registration No. 31,516
 Cynthia G. Seal, Registration No. 39,365

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; 9-15-00 ; 12:40PM ; LEGAL DEPARTMENT-

713-223-1476;# 3

Attorney Docket No. 0085AM/1924/S

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Attorney at Law

PAULA D. MORRIS & ASSOCIATES, P.C.2925 Briarpark DriveHouston, Texas 77042

We hereby declare that all statements made herein of our own knowledge are true and that all statements made on information and belief are believed to be true; and further that these statements were made with the knowledge that willful false statements and the like so made are punishable by fine or imprisonment, or both, under Section 1001 of Title 18 of the United States Code and that such willful false statements may jeopardize the validity of the application or any patent issued thereon.

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September 15, 2000

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